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An eco-profile of thermoplastic protein derived from blood meal Part 1: allocation issues

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Abstract
Purpose A renewable thermoplastic called Novatein Thermoplastic Protein (NTP) has been developed from blood meal—a low-value by-product of the meat processing industry. The aim of this research was to develop a non-renewable energy and greenhouse gas emission eco-profile for cradle to gate production of NTP. Environmental impacts of supplying blood meal as a raw material were investigated using different allocation methods for farming and blood meal production. These included mass, economic, treating low-value by-products as waste and system expansion by substitution. In part 2, the entire system will be analysed on a cradle to gate basis and include the production of thermoplastic (NTP).
Methods A theoretical NTP production facility was analysed for non-renewable primary energy use and greenhouse gas emissions. Data for feedstocks and process steps were obtained from published papers, government agency reports and engineering models. Mass and economic allocation models treating low-value by-products as waste and substitution were applied, and a sensitivity analysis was used to evaluate the impact of different methods of allocation on environmental impact.
Results and discussion Non-renewable energy use in blood meal production varied between 5 (substitution) and 38 MJ (simple mass allocation) per kg of NTP. Greenhouse gas emissions varied between 0.4 (substitution), or even less if the biogenic carbon content is considered a credit, and 14 kg (mass allocation) CO_2e per kg NTP.
Conclusions It was concluded that both mass allocation and a waste assumption should be considered for the cradle to gate system. Mass allocation is common in other attributional studies and allows for a more transparent comparison. The most appropriate treatment of allocation in an attributional profile was to consider blood as a waste with regard to farming and meat processing, but include blood drying. This takes into account the motivations for farming and meat processing, but also recognises that there are other treatment options for blood that do not produce blood meal used in manufacturing NTP. This would allow NTP to be compared to other bioplastics as well as identifying hot spots in its cradle to gate production. It was also anticipated that results may be adapted in future cradle to grave assessments as product systems are developed.

Keywords Allocation · Bio-based materials · Bioplastic · Biopolymer · Blood meal · Cradle to gate · Life cycle assessment

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1 Introduction

Traditional plastics are derived from petroleum feedstocks giving rise to concerns about non-renewable resource depletion and environmental impact. This has led to first generation bio-based polymers being developed from renewable biological feedstocks such as plants and crops. Using crops for polymer feedstocks, however, competes for land normally used for food production and growing demand for biofuels.

Second generation bio-based polymers use alternative renewable feedstocks such as waste streams or low-value by-products from meat, food processing and agricultural industries. Blood meal is one such feedstock. It is a by-

product of the meat processing industry, produced by steam drying animal blood collected from abattoirs. It is largely inedible, highly cross-linked and insoluble and is used as a low-value fertiliser. Novatein have developed a chemical treatment using sodium sulphite, sodium dodecyl sulphate, urea and a plasticizer that overcomes interactions between the protein chains and allows blood meal to be processed as a thermoplastic (Novatein Thermoplastic Protein or NTP) (Verbeek et al. 2007).

Using a renewable feedstock does not guarantee that a bio-based polymer is environmentally friendly. Considerable amounts of energy can be used to convert renewable biomass into a bio-polymer. In some cases, energy use even exceeds that used to produce the synthetic polymers they replace (Gerngross 1999; Vink et al. 2003), although more recent studies have shown improvements (Akiyama et al. 2003; Harding et al. 2007; Kim et al. 2009; Vink et al. 2007). The energy required must be supplied either by renewable (solar, wind, hydro and bio-gas) or traditional means (fossil fuel and nuclear). In addition, any additives used to produce the bio-based polymer can also contribute to the energy demand and environmental impact of the polymer.

A hypothetical NTP production facility was developed in a commercial feasibility study for Novatein (Smits et al. 2008). This facility was evaluated using life cycle assessment techniques to determine the environmental impact of manufacturing NTP compared to other types of polymers.

Using waste or by-products as feedstocks presents some difficulties in allocating energy demand and environmental impacts in an attributional life cycle assessment (LCA). For example, in the meat processing industry, the environmental burdens from farming, transport and slaughtering can be allocated to the primary products such as meat, secondary products such as leather, tallow and gelbone and waste products, such as blood meal. Allocation could be based on economic value, mass fraction or some other relationship.

Examples of economic allocation in life cycle assessment of agricultural by-products include producing biodiesel from New Zealand tallow (Barber et al. 2007), Catalonian leather (Canals et al. 2002) and Indian leather production (Joseph and Nithya 2009). In the latter example, farming impacts were ignored and allocation was only used for meat processing. Mass allocation methods have been used in LCA of other bio-based polymers such as polyhydroxyalkanoates (PHA) produced from corn dextrose and soy beans (Akiyama et al. 2003), which included impacts of corn wet milling and soybean oil milling.

Alternatively, system expansion can be used to compare multifunctional systems in consequential LCA. For example, other studies of PHA have included a credit for environmental impacts avoided by using co-products from corn wet milling in PHA production as substitute for other materials (Kim and Dale 2005, 2008).

For a cradle to gate eco-profile of the kind published by Plastics Europe, system expansion is avoided. Instead allocation based on mass, economic, energy or stoichiometry is used (Boustead 2005; Plastics Europe 2009). Their eco-profiles of commodity plastics are commonly used as a benchmark for comparing new bio-based polymers. For a valid comparison, consistent methodologies should be applied. For example, the Plastics Europe approach has been used for polylactic acid (PLA) produced by Nature Works™ (Vink et al. 2003, 2007).

Some studies of bio-based polymers derived from waste feedstocks ignored the environmental impact of processes that produced the waste because the feedstock had little or no value. Examples include PLA from municipal food waste (Sakai et al. 2003) and PHA from industrial wastewater (Gurieff and Lant 2007). In the latter example, only “non-renewable CO_2 emission equivalents” were evaluated, which could set a precedent for ignoring any animal methane emissions from farming.

LCA results are dependent on the allocation method and boundaries used. Appropriate allocation of impacts from multifunctional processes is one of the most challenging and most discussed issues in life cycle assessment (Finnveden et al. 2009). As seen above, allocation procedures vary widely in published studies and no clear precedent exists as to the most appropriate method for a bio-based polymer produced from blood meal. The aim of this paper was to examine the effect of different allocation methods on the environmental impact of blood meal used in NTP production and select an appropriate scenario (or scenarios) for cradle to gate eco-profile for NTP.

2 Methods

2.1 Goal definition

The objective of part 1 of this paper is to compare the effect of allocation procedures on the eco-profile of blood meal and select an appropriate methodology for NTP. Part 2 of this paper will use the selected allocation method to estimate a cradle to gate eco-profile of the polymer. Together, these papers present the findings of a cradle to gate study which was conducted with the following objectives:

1. Estimate primary energy use and greenhouse gas emissions in producing blood meal and NTP in a New Zealand context;
2. Identify significant contributions to those environmental impacts; and
3. Compare NTP production to other bio-based polymers.

These data could then be used in future cradle to grave LCA studies on NTP-derived products (Madival et al. 2009).

As the assessment is for a theoretical production facility, the study is not intended for making marketing claims of equivalence or superiority between a product made of NTP and another product that could fulfil the same function. This goal therefore does not fall under the definition of a "comparative assertion disclosed to the public" (Guinée and ebrary Inc 2002).

2.2 Scope

2.2.1 Function

NTP can be used as substitute for petroleum-based polymers for extrusion and injection moulding into useful products. Laboratory-produced NTP has comparable mechanical properties to linear low density polyethylene (LLDPE) and hence can be considered functionally equivalent to LLDPE in several applications (Verbeek and van den Berg 2011).

A commercial feasibility study was conducted on a hypothetical large-scale NTP production plant. In the proposed process (Fig. 1), water is heated by a gas heater and mixed with the denaturants and plasticizers in an agitator. This solution is mixed with milled blood meal in a ribbon mixer before being fed through an extruder. The extruded polymer is pelletized and cooled before packaging (Smits et al. 2008).

The functional unit for this study was the production of 1 kg thermoplastic material that can be injection moulded into products such as single use seedling trays. The reference flow for part 1 is therefore the amount of blood meal necessary to produce 1 kg NTP (0.5094 kg blood meal).

2.2.2 System boundaries and description

The system boundaries and unit processes for which data were collected are shown in Fig. 2. Part 1 considers the processes involved in the production of blood meal to determine which allocation scenarios are to be used in part 2's analysis for of the cradle to gate system.

Farming involves raising cattle for the meat processing industry. Inputs include carbon dioxide and sunlight consumed by grass grown for feed, fuel and electricity for farm activities and nitrogen and phosphate fertilisers for plant growth.

Meat processing consists of slaughtering animals, collecting the blood, removing the offal and cutting up the carcass into meat products. The remainder is rendered into edible and inedible products such as tallow, meat and bone meal and gelbone. The collected blood is steam coagulated, dried and milled into blood meal powder. Although rendering is an essential part of meat processing operations for pollution control, it was considered as a separate unit process in this analysis.

In addition to blood meal powder, several other additives are used in NTP to enable the protein chains to undergo thermoplastic processing. The production systems of each of these materials constitute further unit processes and are discussed in part 2.

2.2.3 Omission of life cycle stages, processes or data needs

As this assessment was performed on a cradle to gate basis, products from NTP, their use and disposal, were excluded. This is a common approach for new bio-based polymers (Harding et al. 2007), particularly when commercial applications have not been developed. The energy used in building the NTP facility was also excluded, as energy needs in day to day operations summed over the lifetime of

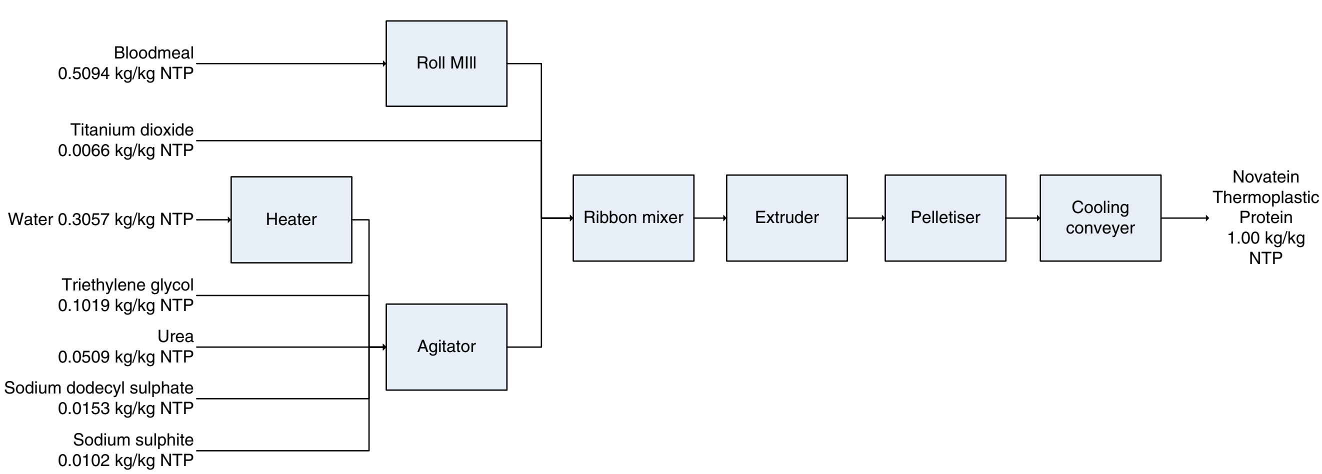


Fig. 1 Proposed commercial process for the production of Novatein Thermoplastic Protein

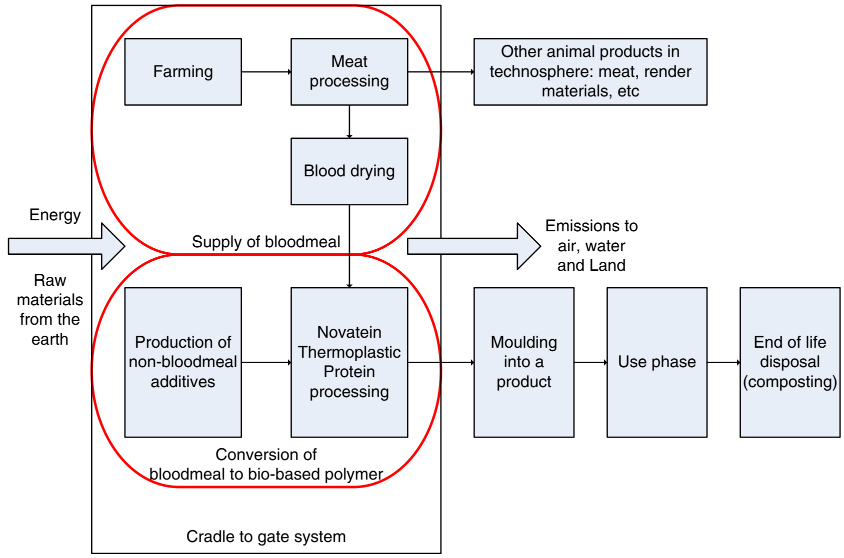


Fig. 2 System boundaries for Novatein Thermoplastic Protein. Part 1 only considers the supply of blood meal

the facility were assumed to be much greater than the energy embodied in constructing the facility (John et al. 2008; revised May 2009).

2.2.4 Impact assessment

Impact assessment was limited to non-renewable primary energy use and greenhouse gas emissions for practical reasons regarding the availability of data for analysis within the time scale of the study. Assessments of other bio-based polymers have focused on these two categories given the motivation in their development was to reduce dependence on non-renewable, oil-based feedstocks (Harding et al. 2007).

Greenhouse gas emissions were included because while first generation bio-based polymers generally use plant-based feedstocks, NTP is manufactured from biomass from ruminant animals which release considerable quantities of methane. Methane emissions from agriculture contributed 47% of the net greenhouse gas emissions for New Zealand in 2007 (Ministry of Economic Development 2009b). GWP100 values for greenhouse gas emissions from IPCC's second assessment report were used for methane, carbon dioxide and nitrous oxides to be consistent with other data sources and comparisons used in this study.

Additional impact categories strongly associated with agricultural activities such as land and water use and eutrophication were beyond the scope of this initial study. Such impacts would be subject to the same allocation issues discussed in this paper and may be explored in future work. It was deemed important to at least determine whether NTP can achieve the goal of a reducing non-renewable energy use prior to any future investigation of additional impacts.

2.3 Major assumptions, choices and simplifications

2.3.1 Electricity

Energy consumption and emissions for electricity used in blood meal production were based on 2008 average New Zealand electricity generation. Sixty-five percent of New Zealand electricity demand is supplied by hydroelectricity, geothermal and wind power (Ministry of Economic Development 2009a), therefore greenhouse gas emissions and non-renewable energy needs are lower than other countries relying on predominantly coal- or oil-based generation. An alternative scenario using a marginal electricity assumption of 100% coal-fired electricity generation was also considered in the sensitivity analysis. Conversion factors for estimating greenhouse gas emissions and primary energy used from delivered energy are given in Table 1 (Barber 2009; Ministry of Economic Development 2009a).

2.3.2 Allocation

The ISO standards on life cycle assessment suggest a stepwise procedure for allocation (International Standards Organisation 2006, Standards Australia/Standards New Zealand 1999):

1. Remove need for allocation using system expansion or subdivision of unit processes. If this is not practical then:
2. Allocate based on the causal relationships between products and environmental impacts. This is not always a simple physical quantity such as mass.
3. Allocate based on other relationships, for example economic value, that reflect the motivations behind performing activities that cause environmental impacts.

Table 1 Conversion factors used to convert delivered energy to non-renewable primary energy and greenhouse gas emissions (Barber 2009) (Ministry of Economic Development 2009a)

Delivered energy type	Non-renewable primary energy ($MJ_{primary}/MJ_{delivered}$)	Renewable primary energy ($MJ_{primary}/MJ_{delivered}$)	Total primary energy ($MJ_{primary}/MJ_{delivered}$)	Greenhouse gas emissions ($kgCO_2e/MJ_{primary}$)	Greenhouse gas emissions ($kgCO_2e/MJ_{delivered}$)
Electricity (2008 average)	1	1.36	2.36	0.02794	0.06597
Electricity using coal (2008 average)	2.77	n/a	2.77	0.09789	0.2712
Coal (lignite)	1.02	n/a	1.02	0.09789	0.09985
Diesel	1.19	n/a	1.19	0.06880	0.08187
Natural gas	1.13	n/a	1.13	0.05395	0.06096

However, when it comes to LCA practice, these steps are interpreted and applied in different fashions. Avoiding allocation by subdivision is only possible when a system can be broken down into single function unit processes (Ekvall and Finnveden 2001). In the case of blood meal, dividing one live animal into multiple products will always be a multifunctional separation. Therefore, subdivision cannot be used to avoid allocation for NTP. Any impacts from single function sub-processes (i.e. blood drying) can be attributed entirely to their functions, leaving only the shared sub-processes (e.g. farming and meat processing) needing allocation (Ekvall and Finnveden 2001).

Farming, transportation to the slaughterhouse and meat processing are related unit processes. The product of farming (a live animal) is transported, then slaughtered and divided into multiple outputs in meat processing. Therefore, in this analysis, allocations for these processes are treated similarly.

The following allocation scenarios for farming and meat processing were considered for blood meal production:

1. Mass allocation based on raw blood being a fraction of live animal weight (simple mass allocation);
2. Mass allocation based on blood meal as a fraction of all animal products, excluding waste and losses (mass allocation excluding wastes and losses);
3. Economic allocation based on the price of blood meal as a fraction of the price of a carcass;
4. A waste assumption with no impacts of farming and meat processing attributed to blood meal. Blood drying was included as there are other treatment options for blood that do not produce blood meal;
5. System expansion, considering the amount of urea required to replace blood meal as a fertiliser; and

The second case listed was chosen as the reference case for sensitivity analysis as mass allocation is common and using the mass of blood meal is more consistent with the principle of dividing outputs that are partly product and partly waste.

2.3.3 Carbon content of blood meal

The removal of carbon dioxide from the atmosphere represented by the biogenic carbon content of blood meal used in manufacturing NTP can be considered as a separate unit process with negative CO_2 emissions (Patel 2005). The mass of carbon dioxide removed from the atmosphere within the system boundaries was assumed to be directly proportional to the mass of biogenic carbon contained within the biomass.

2.4 Data collection

Data on primary energy use and aggregated greenhouse gas emissions were obtained from literature and government agency reports (Table 2) or calculated based on process information. Commercial LCA databases were avoided due to cost, difficulty in checking assumptions and not being specifically for a New Zealand context. Additional assumptions to those mentioned above are detailed in Table 3. The economic values shown and used for economic allocation represent industry-based estimates rather than multi-year averages.

2.4.1 Blood drying

Additional detail on the blood-drying process modelled is given in Fig. 3. The site visited utilises 2 GJ gas and 90 kWh of electricity from the national grid per tonne of raw material entering the plant. As mentioned in Table 3, it has been assumed that energy use per kilogram of raw material is independent of the composition of raw material, i.e. 1 kg of raw diluted blood required the same amount of energy for processing as 1 kg of other render materials.

3 Results

3.1 Non-renewable primary energy use

The allocation scenario used had a large impact on non-renewable primary energy used, ranging from 37 MJ/kg

Table 2 Table of data sources

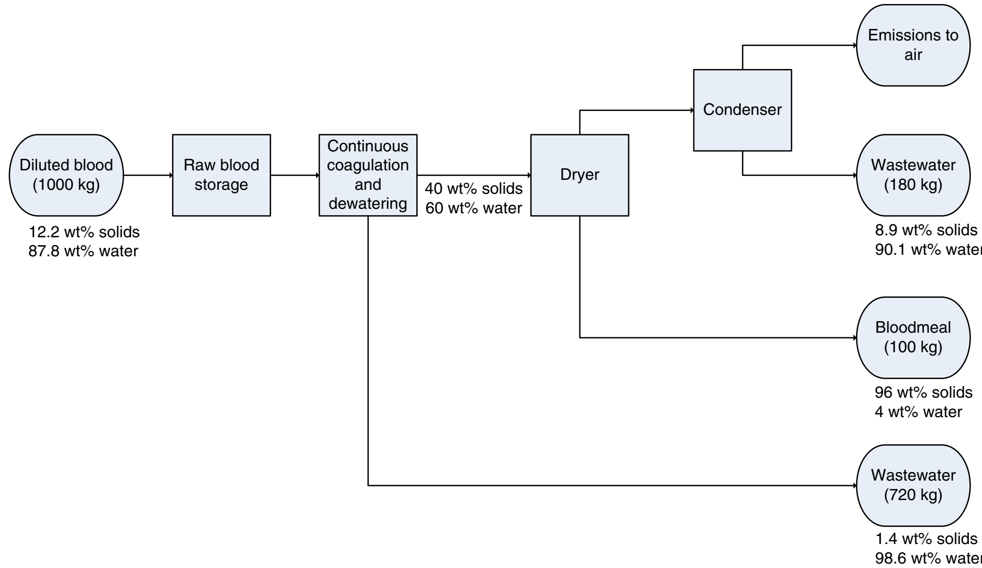
Unit process	Data source	Data collected
Farming	Barber et al. 2007	Total NRPE and GHGs per kilogram of dressed carcass weight and kilogram live weight
Transport to slaughterhouse	Barber et al. 2007	Total NRPE and GHGs per kilogram of dressed carcass weight and kilogram live weight
Meat processing	Barber et al. 2007	Total NRPE and GHGs per kilogram of dressed carcass weight and kilogram live weight
Transport to the rendering facility	Alcorn 2003	NRPE factors for NZ transport
Rendering/blood drying	Site visit and interview with plant manager	Delivered energy required per kilogram of raw material (diluted blood), yield of blood meal from raw material
	Neulicht and Shular 1995	Non-energy ammonia emissions factor per kilogram of blood meal
	European Commission 2007	Alternative delivered energy requirements based on European data
Urea production (for substitution)	Wells 2001	Total NRPE and GHGs per kilogram of N
NZ energy supply	Barber 2009	NRPE and GHGs for various fuels and NZ average electricity
NZ coal-fired electricity	Ministry of Economic Development 2009a	Coal usage and electricity generation to adapt NRPE and GHGs for coal-fired electricity

NRPE non-renewable primary energy, *GHGs* greenhouse gases

Table 3 Table of assumptions

Assumption about	Assumption
Animal composition	3.5 wt.% of live weight is blood (Filstrup 1980)
	15 wt.% of raw blood is recoverable solids (Fernando 1984)
	14 wt.% of live weight is "waste," made up of shrinkage, paunch, manure and unrecovered blood. The other 86% includes the dressed carcass plus by-products such as blood meal, tallow and hides/leather (Filstrup 1980)
	The average animal has a live weight of 500 kg and a dressed carcass weight of 275 kg (Barber et al. 2007)
Economic value	The price of blood meal is approximately NZD $1.00/kg (Smits et al. 2008)
	Approximate value of an entire animal is NZD $5.00/kg carcass weight (Meat and Wool New Zealand 2009)
Fertiliser function	Blood meal fertiliser contains 0.14 kgN/kg blood meal (Yates 2009)
Non-energy emissions from blood drying	Only water vapour and ammonia were considered. Ammonia is oxidised fully to N_2O when passed through biofilters representing a contribution to greenhouse gas emissions
Division of energy demand in rendering plant	Energy use per kilogram of raw material is independent of the composition of that raw material
Transport	Average distance from slaughterhouse to rendering/blood drying plant is 100 km
Geographical coverage	New Zealand
Additional assumptions included in sensitivity analysis	
Marginal electricity generation	100% of the electricity used in blood drying supplied by coal-fired electricity, instead of the New Zealand average
Biogenic carbon credit	Carbon content of blood meal is ignored, instead treated as a credit
International blood drying	Heat and electricity demand for blood drying based on European data (European Commission 2007), instead of the New Zealand site visited
No dilution of raw blood	15% yield from raw material entering blood drying facility, instead of 10%

Fig. 3 Mass balance for drying of diluted blood at the visited rendering plant



NTP on a simple mass base allocation to 4 MJ/kg NTP where only the energy required to produce urea to replace blood meal as a fertiliser was considered (Fig. 4). Farming had the largest impact in the mass-based scenario of 17 MJ/kg NTP, followed by blood meal drying at 13 MJ/kg NTP. Synthetic urea required less energy to produce on a kilogram nitrogen basis than blood drying alone because less urea is required as fertiliser (urea has 47 wt.% nitrogen compared to 14 wt.% nitrogen in blood meal). Table 4 compares the results for the supply of blood meal required to produce 1 kg NTP under the different allocation scenarios identified. Percentage variation was calculated relative to "case B" as mass allocation is common, and it accounts for some of the animal being waste.

Figure 4 shows how the totals for non-renewable primary energy in Table 4 are composed by contributions from different unit processes. Blood drying was the main contributor to energy use in all cases except simple mass allocation and system expansion. In addition, due to the hydroelectric, wind and geothermal energy used New Zealand's electricity mix, 2.25 MJ/kg NTP renewable primary energy is used in drying blood meal.

3.2 Greenhouse gas emissions

Using either of the mass-based allocation methods resulted in significantly higher greenhouse gas emissions compared to the other scenarios (Fig. 5). Greenhouse gas emissions

Fig. 4 Non-renewable primary energy use in supply of blood meal for thermoplastic protein production under different allocation scenarios

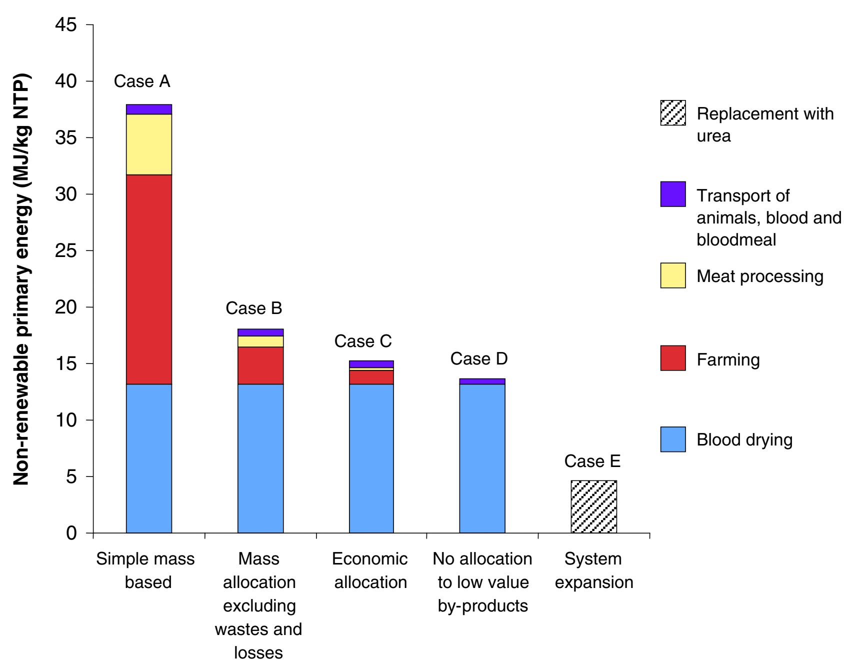


Table 4 Sensitivity of supply of blood meal for NTP manufacture to allocation scenario used for farming and meat processing

Case	NRPE		GHGs (net)		GHGs (excluding biogenic carbon credit)	
	(MJ/kg NTP)	Variance (%)	(kg CO_2e/kg NTP)	Variance (%)	(kg CO_2e/kg NTP)	Variance (%)
Simple mass allocation for raw blood	37.93	110	13.49	493	14.52	340
Mass allocation for blood meal, excluding waste and losses	18.06	0	2.27	0	3.30	0
No allocation for low-value by-products	13.68	−24	−0.20	−109	0.83	−75
Economic allocation	15.22	−16	0.67	−70	1.70	−49
Substitution with urea	4.64	−74	−0.81	−136	0.21	−94

Percentage variance has been calculated relative to case B

NRPE non-renewable primary energy, *GHGs* greenhouse gases

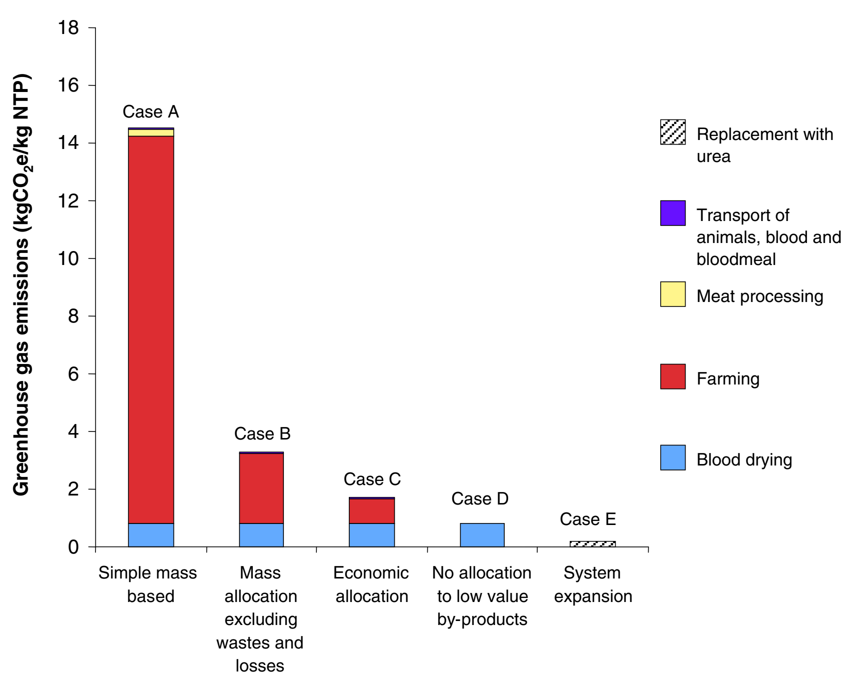
from farming contributed close to 95% of the total emissions in case A and about 75% in case B, mainly due to enteric methane emissions from the animals during their lifetime.

4 Discussion

4.1 Allocation in farming and meat processing

It was found that the allocation scenario used had a large impact on non-renewable energy use and greenhouse gas emissions calculated for blood meal. In practice, allocation by mass of co-products is common and easy to apply (Patel 2003). However, simple mass partitioning should be avoided for some types of process as it can lead to absurd results. For example, in a case of sodium hydroxide production with minimal excess inputs, simple mass partitioning of inputs across all products could mean that the mass of sodium allocated to sodium hydroxide is less than the amount required by the stoichiometry of the chemical reaction (Boustead 2005). Specifically, for the blood meal system, simple mass allocation does not take into consideration that the motivation for beef farming is meat production, not a low-value by-product such as blood meal. Mass allocation also requires a decision as to which masses should be used as a basis (e.g. live animal weight, carcass weight, total mass of products, etc.). This is complicated with the downstream separation of an output from one unit process into wastes and products as is the case with the production of blood meal. If whole blood is considered as a product of farming and meat processing

Fig. 5 Contribution of blood meal to greenhouse gas emissions of NTP production under different allocation scenarios for farming and meat processing



before drying, the mass used for allocation in calculations is six to ten times larger than if only the solids recoverable after the separation are considered a product.

Economic allocation is sometimes used to allocate environmental impacts where an activity is motivated by production of a main product (such as meat), but also produces other products of some value (such as leather, tallow and blood meal). One of the difficulties with economic allocation is the selection of an appropriate price for each product. New uses of a product may result in additional demand, thereby causing an increase in price. For example, protein recovery techniques, other than production of blood meal, exist for blood which results in higher value products (MIRINZ 1985). Another shortcoming of economic analysis is that prices vary based on a large number of factors independent of the manufacturing process. Economic fluctuations are not constant between co-products either. For example, blood meal may drop in price at the same time as meat prices increase. The impacts attributed to products can therefore change without any change in the technology or process used (Boustead 2005).

Alternatively, mass allocation can be used for main products, with no allocation to low-value by-products, essentially treating them as wastes (Patel 2003). Under such a procedure, emissions and process energy of farming and meat processing are allocated entirely to the main products such as meat and not to blood meal. Transport of blood to the rendering facility and drying blood are all that is attributed to blood meal (as shown in Figs. 4 and 5). Such a procedure could be justified if the total impacts from a unit process are dependent solely on demand for the main products. That is, if the total amount of farming and meat processing is independent of demand for blood meal. The weakness of such an approach is that the results for the main product do not clearly distinguish between processes where a low-value by-product is disposed of instead of being used. Under such an allocation, the greenhouse gas emissions or energy use of farming and meat processing attributed to meat would be identical whether blood meal was used for something or not. Other impact categories beyond the scope of this assessment, for example eutrophication, may, however, show a distinction if the blood was dumped or treated in a wastewater facility.

The fifth approach shown in Figs. 4 and 5 is a form of system expansion by substitution, i.e. using urea as a fertiliser to replace blood meal now being used to make plastic. System expansion can be useful in consequential comparative LCAs for decision-making. However, like economic allocation, it relies on factors (e.g. urea production technology) outside of the technical coverage of the system being investigated. As such, it has been criticised as inappropriate for an attributional LCA, such as an eco-profile of plastics (Boustead 2005), as the impacts attributed to the plastic can change without any changes in the how that plastic is produced. The recently published ILCD handbook, however, suggests system expansion can be used in an attributional LCA under specific circumstances. In particular, the handbook considers that system expansion by substitution is applicable for attributional models that include existing interactions to other systems such as credits for avoided primary production in existing recycling systems. Nevertheless, elsewhere the handbook states that in cases where subdivision cannot provide solely mono-functional processes, “allocation is the corresponding method approach under attributional modelling for solving multifunctionality of processes,” (European Commission—Joint Research Centre—Institute for Environment and Sustainability 2010).

If the demand for blood meal can be met by blood supply from existing farming activities, it is reasonable to assume the total emissions from farming are dependent on change in supply of meat, rather than change in demand for blood. This would justify the scenario where no energy use or greenhouse gas emissions from farming and meat processing are attributed to blood meal. Such a scenario results in considerably fewer emissions (0.83 kg CO_2e/kg NTP vs. 3.3 kg CO_2e/kg NTP) per kilogram of polymer than mass allocation (see Figs. 4 and 5).

The intended purpose of blood drying is to reduce wastewater biological oxygen demand by removing solids, rather than production of a product. Historically, producing an additional revenue stream from blood drying has been regarded as a bonus (Swan 2000), although this may have changed over the last decade as many meat companies rely on the revenue generated by rendering.

Blood drying alone uses 25.8 MJ/kg NTP non-renewable primary energy (NRPE) and has emissions of 1.55 kg CO_2e/kg NTP, even without including upstream impacts of farming and meat processing. This is around three times the energy and emissions from producing urea to deliver the same amount of nitrogen as shown in Fig. 4. This supports classifying blood meal as a waste with regard to farming and meat processing in LCA.

4.2 Allocation to blood drying within rendering

If blood is considered a waste, it could be argued that the environmental impact of blood drying should also be allocated to the main products such as meat. However, the principle of subdivision to avoid allocation where possible supports treating this as a separate unit process from meat processing, entirely attributed to blood meal. Such a division also recognises that there are alternative waste treatment options for blood.

As blood drying and rendering occur in the same plant, utilities such as steam generation and electricity, filtration

of odourous air and wastewater treatment are shared throughout the whole facility and therefore deemed multi-functional sub-processes. Eliminating allocation via subdivision is therefore not possible within the rendering plant (Ekvall and Finnveden 2001). Energy use in the rendering facility was reported per tonne of raw material entering the plant. Data were not available for blood-drying equipment in isolation. Therefore, energy use was assumed to be independent of the ratio of render material to diluted raw blood. Direct emissions from blood drying have been calculated separately for that process alone (see Fig. 5).

The NZ rendering plant visited utilised 2 GJ gas and 90 kWh of electricity from the national grid per tonne of raw material entering the plant (personal communication with plant manager, 2009). In order to establish the international relevance of this data, the process was compared to data sourced from the Danish Life Cycle Inventory (Nielsen and 2.−0 LCA Consultants 2003). In this database, the energy requirements of plants producing bone, blood and meat meals as 82 kWh electricity and 1.9 GJ fuel per tonne of abattoir waste (Nielsen and 2.−0 LCA Consultants 2003).

The European Commission's best-practice-document for the animal by-products industry estimated requirements to be 120 kWh electricity and 2.4 GJ of fuel oil for an unspecified blood-drying process (European Commission 2007). In the same report, average energy requirements of four general rendering plants were reported to be 83 kWh electricity and 2.5 GJ fuel oil. They also considered different rendering technologies and found the energy requirements ranged between 68 and 91 kWh electricity and 1.8–3.6 GJ fuel oil. This shows that the NZ plant energy usage was in a similar range to international rendering and blood-drying facilities.

4.3 Sensitivity analysis

As well as allocation scenario described above, the effects of other factors on NRPE and GHG of blood meal supply were considered (Table 5). These included electricity generation mix, removing carbon credits, heat and electricity demand in blood drying and blood dilution. Variations of more than 10% were deemed to be significant.

Assuming coal-fired electricity is used in blood drying increases non-renewable energy use by 16% and greenhouse gas emissions by 12%. Electricity generation is therefore a significant assumption with respect to this portion of the life cycle. If blood meal is to be sourced internationally, the electricity supply in the country of origin needs to be considered.

Excluding negative greenhouse gas emissions representing biogenic carbon content of blood meal had no effect on non-renewable primary energy use, but increased net emissions by 45% relative to the reference case. In a full cradle to grave system, the carbon content of blood meal used for making Novatein Thermoplastic Protein may be released back into the atmosphere. Omission of the "carbon credit" therefore can approximate a basic cradle to gate plus grave scenario, given that no additional emissions are generated in end of life disposal.

Sensitivity to data for blood drying was investigated by using an alternate energy demand of 120 kWh electricity and 2.4 GJ heat per tonne raw material (European Commission 2007). The alternate figure used was for blood drying only, rather than for a whole rendering facility, but the technology used to dry blood was not stated. Different technologies for blood processing have different energy demands (Swan 2000). As such, it is not clear whether the variance is due to blood drying using a higher proportion of rendering plant energy, inherent variability between drying facilities or different drying technologies. The assumption is significant with regard to NRPE, causing a 16% increase relative to the base case, but not significant for greenhouse gas emissions with an increase of only 4%.

Energy use in blood drying has been calculated on the basis of the amount of material entering the facility. Diluting blood with wash-water decreases the yield of recoverable solids and increases steam usage in drying (MIRINZ 1985). A different yield of blood meal from the same amount of raw material would therefore cause a different result per kilogram of blood meal. A 10% yield of recovered blood meal from raw material was used in the

Table 5 Sensitivity analysis to additional assumptions about the supply of blood meal

Case	NRPE (MJ/kg NTP)	Variance (%)	GHGs (kg CO2e/kg NTP)	Variance (%)
Mass allocation for blood meal, excluding waste and losses (base case)	18.06	0	2.27	0
100% coal electricity generation	20.99	16	2.55	12
No biogenic carbon credit	18.06	0	3.30	45
Heat and electricity demand for blood drying based on European data	20.91	16	2.37	4
No blood dilution	13.67	−24	1.97	−13

NRPE non-renewable primary energy, *GHGs* greenhouse gases

reference case, based on information about the facility visited. The theoretical yield of blood meal recoverable from undiluted raw blood is 15%. If that yield is used, with the same energy demands per kilogram material entering the facility, the non-renewable energy use in blood meal supply is reduced by 24% relative to the reference case. Emissions are reduced by 13%. The assumption about raw blood dilution is therefore significant. The implication of this is that if blood could be collected more carefully, with a lesser degree of dilution, energy use and emissions from producing blood meal may be reduced.

5 Conclusions and recommendations

A sensitivity analysis showed that the choice of allocation scenario caused the greatest variance in non-renewable primary energy and greenhouse gas emissions for the blood meal production system. Other significant assumptions included electricity generation (coal fired vs. New Zealand average), inclusion or exclusion of a credit for biogenic carbon, data sourced for blood drying and the level of dilution of raw blood prior to drying. Of the allocation scenarios, the assumption that blood is a waste with respect to farming and meat processing is the scenario most reflective of the motivations for NTP development. In this case, only blood drying is attributed to blood meal. Such a scenario reflects raw blood supply being dependent on meat demand whilst acknowledging the existence of other blood treatment methods. This scenario should be considered in the NTP system; however, as allocation method greatly affects outcomes for blood meal, it should not be considered alone.

Mass allocation is commonly used in attributional studies such as eco-profiles of other bio-based plastics and will therefore also be considered for NTP. Two different mass-based allocation scenarios were considered for the cradle to gate system: (a) allocation based on the mass fraction of whole blood amongst total animal live weight and (b) allocation based on the mass fraction of blood meal amongst the total mass of products after waste and losses have been removed. Using the mass of blood meal was more consistent with the principle of dividing outputs that are partly product and partly waste so has been chosen as the preferred of the two. This has been chosen as the reference case for sensitivity analysis, including sensitivity to allocation and electricity scenario. Economic allocation and system expansion can provide some interesting insight; however, they depend on factors outside of the NTP system so these will not be used in the attributional cradle to gate analysis in part 2.

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